PB85-222834

Water-Borne Routes of Human Exposure Through Food and Drinking Water (Revised)

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Prepared for

Environmental Protection Agency, Washington, DC

Apr 83

U.S. Department of Commerce
National Technical Information Service
NTIS

PB85-222834

United States
Environmental Protection
Agency

Office of Water
Regulations and Standards (WH-553)
Washington DC 20460

April 1983
EPA-440/4-85-022

Water

EPA

Water-borne Routes of Human Exposure Through Food and Drinking Water

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50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO. EPA-440/4-85-022	2.	3. Recipient's Accession No. PB85 222834/AS
4. Title and Subtitle: Water-Borne Routes of Human Exposure through Food and Drinking Water			5. Report Date: Final Revision April 1983 6.
7. Author(s): Perwak, J.; Adamson, F.; Gilbert, D.; Scow, K.; and Wallace, D.			8. Performing Organization Rept. No.
9. Performing Organization Name and Address: Arthur D. Little, Inc. 20 Acorn Park Cambridge, MA 02140			10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) C-68-01-3857 (G) C-68-01-5949
12. Sponsoring Organization Name and Address: Monitoring and Data Support Division Office of Water Regulations and Standards U.S. Environmental Protection Agency Washington, D.C. 20460			13. Type of Report & Period Covered: Final 14.

15. Supplementary Notes

Extensive Bibliographies

16. Abstract (Limit: 200 words)

This report discusses methods for identifying and quantifying water-borne routes of contamination of human food and drinking water. The work was performed for the U.S. Environmental Protection Agency (EPA) as part of a program to assess exposure/risk of 65 classes of chemicals (129 "priority pollutants") in the water environment. It is intended as a first step in developing methods for estimating levels of contaminants in food and drinking water resulting from water-borne routes of migration. Points of water contact with food in growth stages, processing, and preparation are identified. A simplified methodology is presented for evaluating pollutant intakes during the growth phase of crops, livestock, poultry, and fish, and information is presented on water use in food processing and home preparation. The routes of contamination of drinking water during treatment and distribution are identified.

17. Document Analysis a. Descriptors

Exposure
Risk
Water Pollution
Food Contamination

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group 06H 06T

18. Availability Statement: Release to Public	19. Security Class (This Report): Unclassified	21. No. of Pages: 62
	20. Security Class (This Page): Unclassified	22. Price

(See ANSI-Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

EPA-440/4-85-022
December 1981
(Revised April 1983)

WATER-BORNE ROUTES OF HUMAN EXPOSURE THROUGH FOOD AND DRINKING WATER

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68-01-3949

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U.S. ENVIRONMENTAL PROTECTION AGENCY
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FOREWORD

This report is part of a series of documents prepared under the Monitoring and Data Support Division's pollutant exposure fate and risk assessment program. This program is directed towards investigating the risks due to presence of 129 Priority Pollutants in our nation's waters.

Some of the reports prepared under this program address specific pollutants. Others, such as this one, are generic in nature and are meant to be tools for use when performing risk assessments on a wide variety of pollutants.

This report investigates pathways through which waterborne pollutants can enter or leave food during various phases of growth, harvesting, processing, and preparation. It addresses the overall potential significance of these pathways.

A companion report, Identification and Evaluation of Waterborne Routes of Exposure from Other than Food and Drinking Water (EPA-440/4-79-016), investigates other means of exposure to waterborne pollutants: inhalation of vapors from polluted waters, and dermal absorption.

A related series of documents assesses the overall risks from 54 of the most important Priority Pollutants. These documents compare the importance of all known exposure routes, environmental pathways, and sources of the particular pollutants.

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1.0 SUMMARY AND CONCLUSIONS

The Monitoring and Data Support Division, U.S. Environmental Protection Agency, is investigating the sources and distribution of 129 priority pollutants in the nation's environment in order to identify populations of humans and biota exposed to these pollutants and to determine the associated health risks. In support of that effort, this task was undertaken to identify and quantify major water-borne routes of human exposure through food and drinking water.

Points of water contact with food have been identified and, to the degree possible, the timing and volume estimated. While it was not possible to arrive at an overall methodology for estimation of contamination, the available information on the extent of water contact, especially in growth, processing and preparation, suggests that this source may be an important route of exposure to humans and livestock.

A simplified methodology has been developed for evaluating pollutant intakes via the water-borne route for food in the growth phase, including crops, livestock, poultry, and fish. Background information on water use in food processing and home preparation is presented that could form the basis for the development of an estimation model in the future. Several steps (some exceedingly complex) are required before actual levels of food contamination resulting from water contact can be estimated:

- Relate yield of crop to total yield of biomass per acre for a better estimate of concentration;
- Quantify pollutant loss rates from food during the growth period;
- Quantify pollutant uptake and loss rates from food during processing and home preparation.

However, in the process of considering food contamination, several water-borne routes of contact were identified as being potentially important, and could result in human exposure to pollutants.

- crop growth -- rainfall or irrigation water
- water consumption of livestock and poultry
- uptake of pollutants from water by aquatic organisms
- water-mixing with food products

The relative importance of these routes cannot be established at this time. In addition, although food processing has been shown to involve large quantities of water, the importance of this route cannot be established since a detailed assessment of the surface area contacted and the time of contact would be required. This would vary by crop and process step.

The routes of contamination of drinking water in treatment and distribution have also been identified. However, a model predicting concentrations in drinking water from these sources was not considered feasible at this time. It appears likely that only specific situations of contamination (i.e., trihalomethane formation, or lead corrosion) could be modeled due to the unique nature of each situation.

2.0 INTRODUCTION

The Monitoring and Data Support Division, U.S. Environmental Protection Agency, is conducting a systematic investigation of the sources and distribution of 129 priority pollutants in the nation's environment in order to determine the exposure and risks to man, fish, and other biota. One part of this program is the preparation of exposure and risk assessments, which identify the populations exposed to specific chemicals and estimate the health risks to man, fish, and wildlife. In the conduct of these risk assessments, it is important to identify and quantify the major water-borne routes of human exposure to pollutants.

This task considers methods for identifying and quantifying water-borne routes of human exposure. The objectives of this task were to:

- Identify water-borne routes of contamination to food.
- Identify routes of contamination in drinking water treatment and distribution.
- Develop a methodology for quantifying the contamination of food and drinking water through the routes identified.

The project was focused primarily on the first two objectives; data limitations meant that the third objective could be addressed only in a very preliminary fashion. In addressing these objectives, several simplifying assumptions were made:

- The pathways of pollutants to the water compartments were not considered.
- The routes of contamination of drinking water supplies were not considered.
- The quality of various sources of water used in food production was not differentiated.
- Pollutant losses occurring in any phase of food production or drinking water treatment and distribution were considered, but not examined in detail.

This task was a first step in estimating inputs of contaminants to food and drinking water. In order to estimate actual concentrations in food, losses would need to be considered, as well as the specific characteristics of each type of food and pollutant.

In order to characterize the routes of contamination of food and drinking water, several steps in the production of food and drinking water were examined. For food, Chapters 3.0, 4.0, and 5.0 examine contamination during growth, processing, and home preparation. Of these areas, contamination during growth is the one that can be characterized most quantitatively at present. A simplified methodology is developed for estimating water, and thus pollutant uptake by crops. Rates of water uptake for livestock, poultry, fish and shellfish are also discussed in Section 3.2.

Chapter 4.0 describes water use in food processing. It identifies types of water contact and estimated volumes used in various processes for different food groups. Water use in home preparation is considered in a similar manner in Chapter 5.0. No attempt was made to develop a methodology for estimating pollutant intake in processing or home preparation, since a multifaceted model would be required, and the information presented in this report is only the first step in the development of such a methodology.

The possible routes of contamination of water supplies during treatment and distribution are considered in Chapter 6.0. Due to the nature of the contamination routes, the development of a general methodology for estimating concentration was not attempted.

3.0 WATER-RELATED CONTAMINATION OF FOOD DURING GROWTH

3.1 FOOD CROPS

3.1.1 Principles of Irrigation and Crop Physiology

This section summarizes the key principles of crop physiology and irrigation practice as background for constructing a preliminary model for food crop contamination by irrigation water. In order to provide a relatively simple method of approximating uptake, pollutant uptake is assumed to occur with water uptake, although this is often not the case. Thus, the resulting model is not an exhaustive theoretical model incorporating all physical and biological processes but rather a simplified method of approximating uptake. Its purpose is to determine the importance of water-borne routes of contamination during crop growth.

3.1.1.1 Irrigation

Optimum plant performance results at least partially from an uninterrupted and adequate supply of water (Janick et al. 1969). The nature of each agriculture site is defined by many factors, including soil horizons, weather regimes, topography, and groundwater hydrology. Because of the inherently wide variation in and numerous possible combinations of these factors, irrigation guidelines have been developed experimentally for specific crops and soil types in various regions of the U.S. The state Extension Services can supply irrigation data, calculated for the specific weather condition being experienced in the region. As an aid to agriculturalists, the Extension Services also maintain data on the rate of crop growth under various weather and irrigation conditions.

Three kinds of water are associated with soil: hygroscopic, gravitational and capillary. Hygroscopic water is the thin film of water tightly bound to the soil particles. This bonding renders the water unavailable to plants. Capillary water fills the spaces between soil particles, is held in place by weak molecular forces, and is available for uptake by plant roots. The third type of water associated with soil is gravitational. This is the water that will be drained by gravity down to the water table or to an impervious sublayer once the spaces between the soil particles have been filled by capillary water. The "field capacity" of a given soil type is defined as the volume of capillary water that remains following the drainage of gravitational water. When the field capacity is used up by withdrawal by roots or by evaporation, the wilting point is reached and plants loose their turgor (the swollen condition of the cell caused by internal water pressure). Since it interrupts the plants' normal physiologic functioning (Janick et al. 1969), loss of turgor is generally avoided.

Moisture is added to the soil by precipitation and irrigation. The effectiveness of precipitation is a function of the intensity and duration of the storm, the air temperature, and the soil absorption capacity at the time of the storm. Following a rainstorm, the resulting available moisture is usually much less than the total precipitation because of evaporative losses and slow infiltration rates of soils. Rain showers delivering less than 1/4 inch are likely to result in high runoff losses and minimal additions to soil moisture. The final soil moisture content, therefore, is reduced by runoff during and following rain events, and by evaporation caused by the action of wind and sun.

Irrigation has been shown to be most effective if applied when 60% of the field capacity has been depleted. The rate of water use by field crops is determined by hours of sunlight, the drying effects of wind, humidity, wind speed and direction, the leaf area, root volume, and temperature. Consumptive use, therefore, will vary widely among plant species, and even widely for a given crop depending upon its growth stage. For example, the highest water requirements for any crop are usually during the flowering stages (Israelson and Hansen 1962).

The amount of readily available moisture is also a function of the soil type. As shown in Table 3-1, the light sandy soils drain easily and, therefore, contain less readily available moisture than the heavier clay soils. The rate of water extraction by plant roots has been determined to be a function of the root density and the gradient in water potential (determined by the concentration of solutes in the root cell or soil and the turgor pressure). Usually the rate of extraction at the surface is greater than subsurface rates because of the greater surface area of roots in the topsoil layers (Janick et al. 1969). Experimental observations indicate that when the depth of the root zone is divided into four equal horizontal subsurface zones, the following fractions of available water are extracted (where D = depth of the roots):

Zone 1 (surface to D/4)	40%
Zone 2 (D/4 to D/2)	30%
Zone 3 (D/2 to 3D/4)	20%
Zone 4 (3D/4 to D)	10%

To aid in making decisions regarding irrigation, indices of consumptive use have been developed. Consumptive use, or evapotranspiration, is the water loss from a unit surface of land directly (evaporation) and from plant surfaces (transpiration) (Israelson and Hansen 1962). These indices are empirically derived constants, which compare the water needs of a variety of crops to one baseline crop for a given region. In Table 3-2 the consumptive use indices of 26 crops are presented for the Western States, using alfalfa as the baseline crop for comparison.

TABLE 3-1. COMMON WATER CAPACITIES OF SOIL BY SOIL TYPES

Soil Description	Readily Available Moisture ("/ft)
light, sandy - coarse to fine	0.7 - 0.9
medium, loamy - fine sandy loam	1.5
silt loam	1.9
heavy, clay - clay loam	2.1
clay	2.0

Source: Janick et al. (1969).

TABLE 3-2. SEASONAL CONSUMPTIVE-USE REQUIREMENTS OF COMMON IRRIGATED CROPS IN RELATION TO THE REQUIREMENTS FOR ALFALFA--WESTERN STATES

Crops	Relation of Seasonal Consumptive Use of Crops listed to the Seasonal Consumptive use of Alfalfa--(Optimum Yield)
Alfalfa	1.00
Almonds[a]	0.42
Apricots[a]	0.50
Artichokes	0.50
Avocados[a]	0.52
Beans	0.42
Berries	0.40
Clover	0.90
Carrots	0.40
Corn	0.65
Citrus[a]	0.70
Cotton	0.65
Grain	0.50 (variable)
Grain-Sorghum	0.35 to 0.40 (variable)
Grapes	0.50
Hops	0.15 (Plant use only)[b]
Lettuce	0.40
Melons	0.90 (variable)
Pasture	0.65
Peaches[a]	0.50
Potatoes--Winter	0.30
Potatoes--Spring or Seed	0.30
Seed Peas	0.82
Sugar Beets	0.60
Strawberries	0.45 to 0.50
Tomatoes	0.60
Walnuts[a]	

[a]Add 20-25% for permanent grass--legume cover.

[b]Water may be applied in addition to that required for growth for the purpose of quality improvement.

Source: Israelsen and Hansen (1962).

Table 3-3 presents data on water use by various crops. The data given are the estimated monthly evapotranspiration amounts (in inches) for field crops grown in the Sacramento Valley. These values do not include water lost through deep percolation or runoff from the field. In the Sacramento Valley, evaporation from the soil accounts for approximately 10-20% of the seasonal total evapotranspiration (Henderson, D.W., Professor of Agronomy, U.C. Davis, California, personal communication 1979). Thus, the total amount of water actually utilized by a given crop over its growing season may be estimated from Table 3-3 by reducing the figure to 80-90% of the seasonal total.

3.1.1.2 Crop Physiology

The rate of water intake by a plant varies with its growth stage as noted above. As measured by evapotranspiration, the intake will increase steadily during the vegetative stage of the plant's growth, the flowering stage occurs near maximum evapotranspiration, and during the fruiting stages, the evapotranspiration begins to drop. Transpiration (water loss from plant surfaces) is virtually at a standstill in annuals when the fruit has completely matured, dried, or fallen from the plant. Figure 3-1 presents the curve for consumptive use of water over the life cycle of an annual crop. The difference between the curves for consumptive transpiration indicates the amount of water evaporated from the soil surface. Note that as the plant matures and the leaf area increases, the proportion of water evaporated from the soil surface diminishes. The amount of water a plant takes in through its roots is much greater than the amount finally retained by the plant; approximately 99% of the water brought into the plant is vaporized from leaf surfaces. Loss occurs mostly through the stomata (80-85%) and through the cuticle (10-15%). The rate of transpiration can be as much as 1.25 g per 100 cm^2 of leaf surface (Israelson and Hansen 1962; Wilson and Loomis 1967).

3.1.2 Contamination Model

Much of the research necessary for a model that completely and accurately follows all the biological and physical processes, is either lacking or ongoing. Hence the present contamination model for water contact through irrigation is extremely simplified. It estimates the volume of water that can be associated directly with the plant. The resulting estimated concentration of the contaminant in the edible portion represents a (not necessarily the only) worst case scenario, but is primarily an attempt to determine the importance of the water-borne route of contamination.

The assumptions made in this analysis are listed below, followed by the resulting conclusions and necessary discussion. The symbols used in the model are shown in Table 3-4.

TABLE 3-3
NORMAL CROP WATER USE[1]
CENTRAL COASTAL PLAINS[2]
EVAPOTRANSPIRATION (CONSUMPTIVE USE) TABLE

Crop and Growing Period[3]	ESTIMATED MONTHLY EVAPOTRANSPIRATION (inches)[4]												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
Artichokes													
6/15 – 4/15	1.7	2.2	3.1	1.8		.7	2.1	3.0	3.5	3.2	2.2	1.4	24.9
7/1 – 5/1	1.7	2.2	3.1	3.8			1.7	2.4	3.0	3.2	2.2	1.4	24.6
7/15 – 5/15	1.7	2.2	3.1	3.8	2.1		.8	1.9	2.5	2.9	2.2	1.4	24.6
Broccoli													
2/1 – 5/15		1.4	2.5	3.9	2.2								10.0
3/15 – 7/1			.9	2.3	4.3	4.9							12.4
8/15 – 12/1								1.1	2.1	3.0	2.2		8.4
10/15 – 3/1	1.8	2.2								.9	1.4	1.4	7.7
Brussels Sprouts													
4/15 – 8/15				.9	2.6	4.6	5.3	2.3					15.7
7/15 – 3/1	1.8	2.2					1.2	2.4	3.4	3.3	2.2	1.5	18.0
Carrots													
12/1 – 3/31	1.5	2.3	3.3									1.0	8.1
1/15 – 5/15	.5	1.4	3.1	4.1	2.3								11.4
7/15 – 12/15							1.1	2.5	3.4	3.5	2.3	.8	13.6
Cauliflower													
5/15 – 8/1					1.1	3.2	5.2						9.5
8/1 – 11/15								2.1	3.4	3.3	1.2		10.0
12/1 – 5/1	1.5	2.2	3.1	3.9								1.0	11.7
Celery													
1/15 – 7/1	.6	1.5	2.9	4.1	4.9	5.1							19.1
8/1 – 1/1								2.0	2.5	3.2	2.3	1.5	11.5
Cucumbers													
3/15 – 6/15			.8	2.1	4.1	2.2							9.2
7/1 – 8/31							2.9	4.4					7.3
Lettuce													
12/15 – 4/15	1.6	2.1	3.1	1.8								6	9.2
3/15 – 7/15			1.3	3.1	4.4	4.8	2.5						16.1
8/15 – 11/15								1.7	3.2	3.2	1.2		9.3
Onions													
2/15 – 9/15		.7	2.0	3.7	4.7	4.9	5.3	4.7	1.8				27.8
3/1 – 10/1			1.7	3.0	4.6	4.9	5.3	4.8	3.6				27.9
3/15 – 10/15			.9	2.3	4.4	4.9	5.3	4.8	3.9	1.5			28.0
Peppers													
2/15 – 9/1		.7	2.0	3.6	4.7	4.9	5.3	4.6					25.8
4/1 – 11/1				1.6	3.1	4.7	5.3	4.8	3.9	3.1			26.7
Potatoes													
4/1 – 8/31				2.4	4.9	6.1	6.4	3.2					23.0
6/15 – 12/1						1.4	4.2	5.7	4.8	4.1	1.6		21.8
Spinach													
9/15 – 11/15									.9	2.4	1.2		4.5
11/15 – 1/31	1.7										.6	1.2	3.5
1/15 – 4/15	.6	1.6	3.1	1.8									7.3
Tomatoes													
3/1 – 7/31			.8	1.5	4.4	5.8	5.0						17.5
5/1 – 10/15					1.2	1.9	5.0	5.7	4.3	1.6			19.7

[1] Estimated evapotranspiration (Consumptive Use) data were obtained from historic measurements, and from calculations based on data in Figure 8, Table 22 and 23, Crop Water Requirements, No. 24 Food and Agricultural Organization of the United Nations.

[2] Coastal areas of San Mateo, Santa Cruz, Monterey, San Luis Obispo, and Santa Barbara Counties.

[3] Planting to harvest.

[4] Other crops which have similar growing seasons, ground cover, and growth characteristics have similar ET requirements.

Source: Anonymous (und.)

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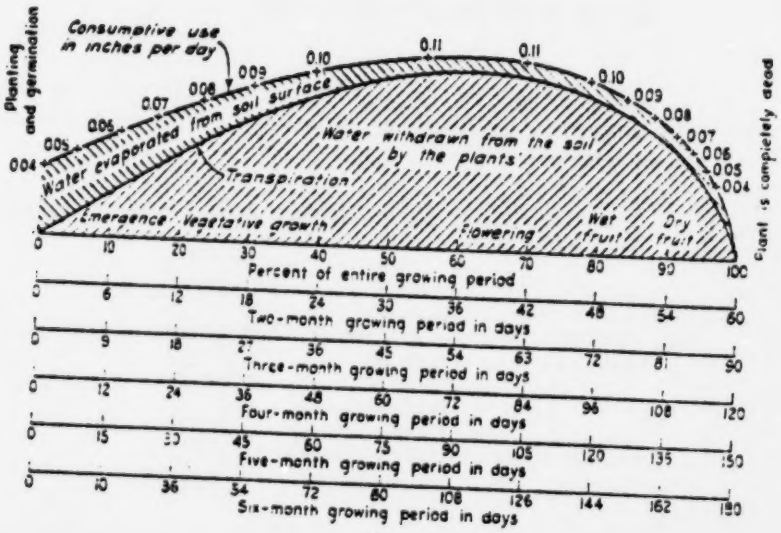


Source: Israelson and Hansen (1962).

FIGURE 3-1 CONSUMPTIVE USE OF WATER BY AN ANNUAL PLANT DURING VARIOUS PERIODS OF GROWTH

TABLE 3-4. SYMBOLS USED IN FOOD CROP CONTAMINATION MODEL

Symbol		Description
V_{ET}	=	total volume in liters of a crops consumptive use of water or evapotranspiration for a given area in its lifetime
V_T	=	volume in liters of water utilized by the crop for a given area in its lifetime ($0.9\ V_{ET}$)
p	=	concentration (mg/l) of the pollutant in irrigation water or rainwater (assumed to be the same as in groundwater)
P	=	mass in kg of a pollutant available in a given area $P = p\ V_T$
$[p]_{FP}$	=	concentration of the pollutant in the plant and thus in the food part
	=	$\frac{P\ (kg)}{\text{biomass per unit area (kkg)}}$
$[p]_{FP*}$	=	concentration of the pollutant concentrated in the food part
	=	$\frac{P\ (kg)}{\text{crop yield (kkg)}}$

3.1.2.1 Assumptions

Assumption: Farmers will seek to maximize yield by keeping the water content of their fields above 60% of field capacity.

Conclusion: The applied volume of water will be sufficient to provide for drainage (gravitational water), runoff, irrigation efficiency, and the volume (in liters) equal to evapotranspiration (V_{ET}).

Discussion: While V_{ET} will obviously vary, depending upon the cost of water, drought, irrigation practices, accidents, etc., it is an adequate description of the ideal situation.

Assumption: Approximately 10% of V_{ET} will evaporate.

Conclusion: $V_T = 0.9V_{ET}$
where V_T=volume of water utilized by plants

Discussion: This value was found for the Sacramento Valley area, and does not apply everywhere. It will be used here as an example.

Assumption: The total mass of pollutant applied to a given field is a function of its concentration in the total volume of water applied (either irrigation water or rainfall).

Conclusion: The total amount of pollutant in the field that is available to plants is that contained in the volume (V_{ET}). So, if the pollutant concentration is [p], then the total amount of pollutant (P) available to the plant is $P = [p] \cdot V_{ET}$.

Discussion: While P is the total amount of pollutant potentially available to the plant, it does not take into consideration adsorption of the pollutant onto soil surfaces, release of pollutant from soil into groundwater, biodegradation in the soil, etc.

Assumption: The transport of pollutant will occur at the same rate as water transport.

Conclusion: The amount of pollutant entering the plants will equal the amount available in V_{ET} that is, P.

Discussion: Although pollutant transport rates are known to vary, this method provides a simple way of estimating pollutant uptake, and gives a rough estimate.

Assumption: Once the pollutant is in the plant, its mass will not be diminished through evaporation or by metabolism.

Conclusion: The concentration in the plant will be given by P/biomass for the same area.

Discussion: Again, this is meant to be a worst case assumption, since both volatilization and degradation may occur. The relative importance of those removal processes would depend on the chemical and the particular plant considered.

Assumption: For the purposes of a simple model, it is assumed that concentrations in the plant and the edible portion are the same.

Conclusion: $[P]_{FP} = \frac{P(kg)}{\text{biomass (kkg)}}$

where $[P]_{FP}$ = concentration in food part.

Discussion: This concentration may be too low in some cases. As a maximum, or for lack of information on crop biomass, the pollutant can be associated with the food part:

$$[P]_{FP}^{*} \quad \frac{P(kg)}{\text{crop yield}}$$

3.1.2.2 Sample Applications

Cadmium Contamination of Cucumbers

Region: California Central Coastal Plains

Growing Season: 3/15-6/15

Procedure	Example
a. Find the volume of water that is taken up and transpired by the crop plants on 1 acre, e.g., find V_{ET}.	ET = 9.2 in.
	$V_{ET} = 9.4 \times 10^{5}$ l/acre
• Find ET for crop and region from Agricultural Extension Service data.	

b. Determine (choose) concentration of pollutant.

- Search STORET or other ambient water data files for an average or high concentration for the region.

0.03 mg/l is maximum concentration of cadmium measured in groundwater (Battelle 1977).

c. Find P -- the amount of pollutant carried into the plants on one acre.

$P = [p] \cdot V_T$

$V_T = 0.9V_{ET}$

$P = 0.03 \text{ mg/l } (9.4 \times 10^5 \text{ l/acre})(0.9)$

$= 25 \text{ g/acre}$

d. Determine yield of crop (kg/acre) for the growing seasons (USDA 1978).[a]

$Y = 13.24 \text{ tons/acre}$

$= 12011 \text{ kg/acre}$

e. Associate pollutant load with crop yield.

$[p]_{FP}^* \frac{25 \text{ g}}{12011 \text{ kg}}$

$= 2 \text{ mg/kg}$

From this example, at a concentration of 0.03 ppm (30 ppb) cadmium in irrigation waters, cucumbers may accumulate cadmium to a level of 2.0 mg/kg.

Cadmium Contamination of Tomatoes

Region: California Central Coastal Plain

Growing Season: 3/1-7/31

a. ET = 17.5 in.

$V_{ET} = 1.8 \times 10^6$ l/acre

b. [p] 0.03 mg/l

c. $P = 0.03 \text{ mg/l } (1.8 \times 10^6 \text{ l/acre})(0.9)$

$= 50 \text{ g/acre}$

d. Yield = 13.75 tons/acre = 12,473 kg/acre

e. $[p]_{FP}^{*} = \frac{P}{Y} = \frac{50}{12473} = 4$ mg/kg

Di-2 Ethyl Hexyl Phthalate (DEPH) Contamination of Iceberg Lettuce

Region: California Central Coastal Plain

Growing Season: 3/15-7/15

a. ET = 16.1 inches

$V_{ET} = 1.65 \times 10^{6}$ l/acre

b. [p] = 3.8 µg/l is the maximum found in ambient water in this part of California according to STORET. The 50th percentile concentration for the country (the median) is 0.85 µg/l (A.D. Little 1981), but the maximum concentration is used as a worst case.

c. P = 3.8 µg/l $(1.65 \times 10^{6}$ l/acre)(0.9)

= 5.6 g/acre

d. Y = 11.75 tons/acre = 10,659 kg/acre

e. $[p]_{FP}^{*} = \frac{P}{Y} = \frac{5.6 \text{ g/acre}}{10,659 \text{ kg/acre}} = 0.5$ mg/kg

3.1.2.3 Limitations of Model and Comparison of Model Results with Monitoring Data

The discussion above shows that there are many gaps in the data necessary to develop a comprehensive model for uptake of waterborne pollutants by food crops. The simple model developed is meant to provide a first approximation of contaminant levels in field crops. Though it is likely that the model will generally overestimate concentration, in some cases it may underestimate, for example, for a compound that is actively taken up by a plant and is not lost through volatilization or degradation.

In summary, the major assumptions, and sources of uncertainty, are as follows:

- No losses or gains of the pollutant to the soil (through leaching, dissolution, or adsorption) are allowed.
- The uptake of the pollutant is assumed to be equivalent to the uptake of water.
- No losses from the plant are considered; i.e., all of the pollutant that enters the plant remains there.

- The pollutant is evenly distributed to the plant parts (including the edible portion).

The results of the sample applications of the model suggest that waterborne routes of contamination can be very important for field crops. Though the estimated concentrations are not expected to reflect accurately real situations, it is useful to compare the model results for cadmium with actual measurements shown in Table 3-5. The estimated concentrations of cadmium are substantially higher than measured concentrations.

The possible reasons for this difference are numerous. First, worst-case assumptions were made in many cases, especially with regard to the concentration in irrigation water. In addition, cadmium is bound to the soil to some extent and hence unavailable for uptake. Measured concentrations of DEHP in lettuce were unavailable, but concentrations of this compound in other foods are generally less than 0.5 µg/kg (Arthur D. Little 1980).

3.2 LIVESTOCK AND POULTRY

Livestock come into contact with water via two routes: ingestion and dermal absorption. The following section estimates the total volume of water to which four of the most common livestock species -- cattle, sheep, swine and poultry -- are likely to be exposed. This provides a first approximation of the mass of a priority pollutant potentially available to livestock over their lifetime as a function of water uptake. In order to estimate tissue concentration, further information would be necessary on distribution, metabolism, and excretion of the pollutant. Again, the goal is to determine the potential importance of waterborne routes of exposure by estimating the upper limit of the amount of a pollutant via water each species can possibly be exposed to in their lifetime.

3.2.1 Ingestion

Water intake must compensate for water loss in respiration, sweating, urination and defecation. Losses will be greater under certain environmental conditions (low humidity, high temperature) and require increased water consumption. Table 3-6 presents estimates of average water consumption per day for several livestock species. The water consumption figures given are approximate values, and represent average rates over a variety of climatic and regional conditions.

3.2.2 Dermal Absorption

With the exception of horses, most livestock found in the U.S. have only a slight ability to sweat (Brody 1964). When subjected to a high ambient temperature, cattle and swine in particular are not very effective at lowering their basal temperature and respond only by panting, a less efficient heat-loss process than sweating. As a result,

TABLE 3-5. COMPARISON OF ESTIMATED AND MEASURED CADMIUM RESIDUES IN FOOD CROPS

Crop	Method	Result (mg/kg)	Source
Cucumbers	Calculated	2	This report
Cucumbers	Measured	0.005	Stoewsand[a] (1980)
Cucumbers in sludge/amended soil	Measured	0.02	
Garden fruits	Measured	0.01 (max)	FDA (1977)
Tomatoes	Calculated	4	This report
Tomatoes	Measured	0.025	Stoewsand (1980)
Tomatoes	Measured	0.6	Stoewsand (1980)

[a]Includes green peppers, tomatoes, cucumbers, etc., in a composite sample.

TABLE 3-6. AVERAGE DAILY WATER CONSUMPTION OF POULTRY AND LIVESTOCK

Species	Daily Consumption (Gallons)	(Liters)
Beef Cattle (all ages; range and feedlot, etc.)	10	38
Dairy Cows (in milk)	13	49.4
Lambs (on feed)	0.4	1.52
Swine (all but boars)	0.9	3.42
Chicken		
Broilers	0.033	0.13
Layers	0.064	0.24
Turkeys	0.082	0.31

Source: Arthur D. Little, Inc., estimates.

temperatures commonly encountered during summer will cause heat stress and decreased productivities in these animals. Figure 3-2 shows a sharp decline in various productivities in cattle at temperatures above 18°C. In hot environments, two management practices are commonly used to cool animals: wet blankets and hosing down. Wet blankets, made of moisture-holding material, are placed on animals during the middle part of the day (at peak temperature) throughout the summer months. Hosing is the direct spraying of animals with water.

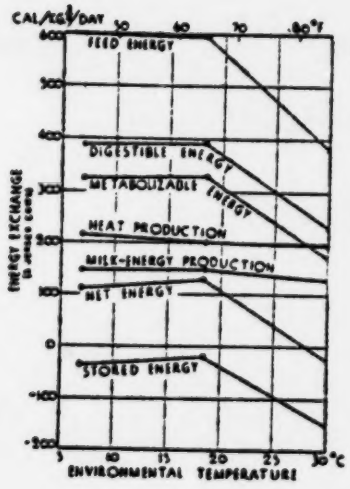
In the hotter regions of the U.S., the exposure period to water used for cooling purposes is estimated to be from 10:30 a.m. to 4:30 p.m. for a total of 6 hours per day (Currie, B., Prof. of Environmental Physiology, Dept. of Animal Science, Cornell Univ., Personal Communication 1980). As an upper limit, the maximum number of days per year when cooling with water is required is estimated to be 90 days (July-September). Therefore, the maximum period of exposure to water is 540 hours per year per capita.

As a worst case, cattle, sheep and swine are all assumed to require dermal contact with water for cooling purposes. Poultry are assumed to find relief from the heat through panting or artificial temperature regulation in their housing.

Calculating the amount of water absorbed through the skin during the period of exposure to water requires data on the body surface area and a skin absorption coefficient for each species. Table 3-7 presents average surface areas calculated for swine, sheep, and dairy and beef cattle. These values are based on a large, full-grown animal to provide an upper limit.

Skin absorption coefficients for water uptake specific to each species were not available. As an approximation of these coefficients, data for human skin were used (U.S. EPA 1979), although the hairless skin of man would presumably have a higher potential for absorbing water than the hides of swine, sheep, and cattle. Hair cover acts as an initial external barrier, and animals constantly exposed to water via a wet blanket or hosing will have saturated fur, which will not prevent water absorption. A more important parameter in determining absorption may be the fiber weave pattern making up the skin collagen and this varies according to the species (Yates 1971).

The water flux through human skin was estimated to be 0.2-0.5 mg/cm^2/hr (Scheulpein and Blank 1971). As a first approximation of water absorption in livestock, a rate of 0.3 mg/cm^2/hr was multiplied by the surface area of each livestock species and the duration of daily water exposure (1.5 hrs/day), in order to estimate daily water uptake through skin. Table 3-8 presents the results.



Source: Brody (1964).

FIGURE 3-2 **INFLUENCE OF ENVIRONMENTAL TEMPERATURE ON FEED CONSUMPTION, HEAT PRODUCTION, AND FEED UTILIZATION IN DAIRY CATTLE**

TABLE 3-7. REPRESENTATIVE BODY SURFACE AREAS AND WEIGHTS FOR VARIOUS LIVESTOCK SPECIES

Adult Species	Equation to Calculate Surface Area	Weight (kg) (W)	Surface (m^2) Area (S)
Swine	$S = 0.10\ (W)^{0.63}$	250	3.24
Sheep	$S = 0.12\ (W)^{0.57}$	70	1.35
Cattle (beef)	$S = 0.13\ (W)^{0.56}$	700	5.10
Cattle (dairy)	$S = 0.12\ (W)^{0.60}$	500	5.00

Source: Brody (1964).

TABLE 3-8. ESTIMATES OF DAILY WATER ABSORPTION THROUGH SKIN OF VARIOUS LIVESTOCK SPECIES

Species	Estimated Water Absorption (g/day)
Swine	15
Sheep	6
Cattle (beef)	23
Cattle (dairy)	23

3.2.3 Comparison of Two Exposure Routes

This analysis indicates that ingestion of water may be a far more significant exposure route for swine, sheep and cattle than dermal absorption (Tables 3-6 and 3-8); for beef cattle ingestion is about 38 kg as compared to 23 g/day for dermal absorption. To the degree that water flux across human skin represents a worst case for absorption across the skin of the three animal species examined, dermal absorption can be ruled out as a significant route.

By contrast, the water consumption by livestock and poultry appears to be an important potential source of contamination. Water consumption represents a larger mass than does food consumption for livestock. For example, for beef cattle, water consumption is about 38 kg, and food consumption (as corn equivalent) is about 7 kg. Thus, based strictly upon considerations of mass intake, water consumption represents a larger source.

3.3 AQUATIC ORGANISMS

For fish and other edible aquatic species constantly immersed in water, water is obviously a primary route of contamination. Considerable research has been conducted on pollutant uptake in aquatic species, and methods have been reported to estimate pollutant uptake (bioaccumulation) for certain groups of chemicals.

The bioconcentration factor (BCF), the chemical concentration in an organism's tissue divided by the concentration in water, is commonly used to express pollutant uptake by aquatic species. This is an equilibrium expression assuming that any further uptake of pollutant is balanced by the depuration, or excretion, rate of the substance. For 36 organic compounds, Kenaga and Goring (1978) derived regression equations relating each chemical's bioconcentration factor to its water solubility and octanol-water partition coefficient. Table 3-9 presents the two equations.

Using these equations to estimate contamination of edible fish species requires that a number of assumptions be made (Kenaga and Goring 1978):

(1) Although considerable species variability in pollutant uptake is common, these equations average data from several fish species and it is assumed that they are applicable to all fish species as a first approximation.

(2) Although these estimation equations assume concentrations in the fatty portion of the fish, the pollutant is assumed to be evenly distributed throughout the body of the fish. This provides an

TABLE 3-9. REGRESSION EQUATIONS CORRELATING BIOCONCENTRATION FACTORS (BCF) IN AQUATIC SPECIES TO OTHER PARAMETERS

Parameter BCF Correlated with	Regression Equation	Correlation Coefficient (r)
Water Solubility	Log BCF = 2.791 - 0.564 (Log WS)	- 0.72
Octanol-Water Partition Coefficient	Log BCF = 1.495 + 0.935 (Log K_{ow})	0.87

Note:

WS = Water Solubility
K_{ow} = Octanol-Water-partition coefficient

Source: Kenaga and Goring (1978)

upper-limit estimate of tissue residue levels because fat is usually discarded during evisceration and the remaining muscle portion is eaten.

(3) Variability in fish parameters likely to affect pollutant uptake, such as fat content, was assumed to be expressed adequately in the equations.

(4) All fish caught for consumption are assumed to have been chronically exposed to the pollutant and to have reached equilibrium tissue concentrations.

For inorganics, no method exists at this time to estimate the BCF in fish or other aquatic organisms. Metals and other inorganics are commonly detected in fish tissue at high concentrations, but assimilation does not appear to follow a predictable pattern based on the current state of understanding. In addition, species variability in uptake patterns is high. For these reasons, no estimation of inorganic pollutant concentrations in fish was possible.

The waterborne route is very important in determining residues in aquatic organisms. Residues of organics can be estimated from the water concentration and a measured or estimated bioconcentration factor. It should be pointed out, however, that consumption of contaminated food items may also contribute to the body burden of aquatic species in some situations.

4.0 WATER-RELATED CONTAMINATION OF FOOD DURING PROCESSING

4.1 INTRODUCTION

Of the 15 trillion gal of water consumed by the manufacturing industries of the United States in 1973, only 5% was accounted for by establishments processing food and kindred products (Table 4-1), whereas four other major industry groups accounted for a total of 85%. An even smaller quantity, possibly about 1 1/2%, actually came into direct or indirect contact with food products. However, when the nature of the U.S. food processing industry is taken into consideration, it can be seen that this use was spread over an exceptionally broad area of operations, involving a complex set of interrelationships.

The food processing industry in the United States is comprised of nearly 30,000 establishments that run the entire spectrum from the manufacture of bulk commodities in huge quantities, such as fats and oils, starches, and sweeteners, which are basic ingredients for the rest of the industry, to the production of highly processed convenience foods for both retail and institutional markets.

While there are at least 50 food processing firms in the U.S. with over $1 billion annual sales, nearly 50% of total food industry sales are derived from about 22,000 establishments with fewer than 100 employees each. In 1978 the food processing industry employed over 2 million people, and produced shipments worth $230 billion.

In addition to this extreme fragmentation, the food industry is also widely diversified in terms of types of products manufactured and processes employed. The U.S. Department of Commerce has classified this industry into 47 individual subsectors at the four-digit SIC code level. Each of these subsectors is really a complete industry in itself, with its own unique characteristics and distinctions. The "food industry" is, therefore, structurally complex, differentiated and interrelated.

4.2 UTILIZATION OF WATER IN FOOD PROCESSING

4.2.1 Introduction

Water comes into intimate contact with foods during preparation and preservation operations. It is universally used for washing fresh raw foods at various stages of preparation; it serves commonly as a carrier of raw materials between unit processes; and it is the medium through which many unit processes such as soaking, blanching, quality separation, and preheating are applied. Water also serves as an ingredient of formulation or as a principal portion of the brine or syrup added as a packing medium. Through its direct contact with raw foods in preparation and processing, or its indirect contact with foods when

TABLE 4-1. WATER INTAKE OF MAJOR U.S. INDUSTRIES, 1973

Industry	Water Intake (billion gal)	% of Total
Primary metal industries	4,941	33
Chemicals and allied products	4,176	28
Paper and allied products	2,415	16
Petroleum and coal products	1,283	9
Food and kindred products	804	5
Transportation equipment	242	2
Total U.S. industries	15,024	100

U.S. Department of Commerce (1973).

used to wash food processing equipment, water exerts influence upon the efficiency of the processing operations and upon the quality of the finished processed food.

The quantity of water used in food processing is subject to wide variation, depending on the physical characteristics of the raw foodstuffs, seasonality and changes in the product mix. Table 4-2 shows the process water usage by U.S. food industry groups in 1973. For the purposes of this discussion, process water includes water that comes into direct contact with the food in addition to water that is consumed in production. It can be seen that the largest users of process water are the meat and poultry packers, processors of canned and frozen fruits and vegetables, and brewers of malt beverages. Each of these industry groups consumed over 20 billion gal of process water in 1973. A more detailed review of amounts of process water used, and type of use for each major food item, follows below.

4.2.2 Meat Products

The meat products group is the second largest user of process water in the U.S. food industry, accounting for 28% of total usage.

The meat packing industry buys live animals and delivers primal cuts, quarters and sides to meat cutting facilities, which reduce them to retail film-wrapped packages. Use of process water in this sector is mostly confined to washing the carcasses after de-hairing, and washing viscera and major cuts. Much of the water is used for cleaning the facilities and the processing equipment. In addition, water troughs are provided for the animals prior to slaughter. Typically, a packing plant uses about 550 gal of water for every 100 hogs slaughtered.

Water is also used quite extensively in poultry dressing plants. To assist in defeathering the slaughtered birds, they are first immersed in hot water to loosen the feathers. Following the defeathering operation, which is carried out by a variety of machines, the birds are subjected to a strong spray of water to rinse off detached but adhering feathers.

During the evisceration operation, both the interior and exterior of the birds are frequently sprayed with water to remove debris. Following evisceration, the birds are cooled by conveying them through a chilled bath. The chilling is accomplished by either a refrigerated jacket on the tank, or by adding water ice to the water bath. In some operations, water is absorbed by the bird up to the legal limit of 8% of the original weight.

The use of water in the manufacture of sausages and other prepared meats is mostly confined to washing operations following meat cutting and trimming; to curing for varying lengths of time in brine baths; and to process line cleanup. Water is also used in production formulation for the purpose of facilitating grinding, chopping and mixing, and to prevent overheating of the mix. In this case, not more than 3% of water

TABLE 4-2. PROCESS WATER USAGE BY U.S. FOOD INDUSTRY GROUPS. 1973

SIC Code	Industry Group	Process Water Use (billion gal)
20	Food and kindred products	232.1
201	Meat Products	64.5
	Meatpacking plants	36.2
	Poultry dressing plants	22.8
	Sausages and other prepared meats	3.2
	Poultry and egg processing	2.3
202	Dairy Products	11.4
	Fluid milk	6.0
	Condensed and evaporated milk	3.0
	Cheese, natural and processed	1.3
	Ice cream, frozen desserts, butter	1.1
203	Preserved Fruit and Specialties	74.0
	. Frozen fruits and vegetables	27.0
	Canned fruits and vegetables	20.5
	Canned specialties	16.0
	Dehydrated fruits, vegetables, soups	5.3
	Frozen specialties	3.4
	Pickles, sauces, salad dressings	1.8
204	Grain Mill Products	13.4
	Corn wet milling	9.2
	Dog, cat, and other pet foods	1.4
	Cereal breakfast foods	1.0
	Flour, other grain mill products	0.9
	Prepared foods	0.5
	Rice milling	0.3
	Blended and prepared flour	0.1
205	Bakery Products	1.7
	Bread, cake, and related products	1.5
	Cookies and crackers	0.2
206	Sugar, Confectionery Products	19.2
	Raw cane sugar	8.6
	Beet sugar	5.2
	Cane sugar refining	3.6
	Confectionery products	1.8

TABLE 4-2. PROCESS WATER USAGE BY U.S. FOOD INDUSTRY GROUPS, 1973 (Continued)

SIC Code	Industry Group	Process Water Use (billion gal)
207	Fats and Oils	
	Shortening and cooking oils	2.8
	Animal and marine fats and oils	1.1
	Soybean oil mills	0.9
	Other vegetable oil mills	0.6
		0.2
208	Beverages	
	Malt beverages	34.3
	Bottled and canned soft drinks	21.0
	Malt	6.4
	Distilled liquor, except brandy	4.5
	Flavoring extracts, syrups	1.2
	Wines, brandy, and brandy spirits	0.8
		0.4
209	Miscellaneous Foods	
	Canned and cured seafoods, other food preparations n.e.c.	10.8
	Fresh or frozen packaged fish	6.0
	Roasted coffee	1.9
	Manufactured ice	1.8
	Macaroni and spaghetti	1.0
		0.1

Source: U.S. Department of Commerce (1973), and Arthur D. Little, Inc., estimates.

and/or ice may be added to uncooked sausage, while cooked sausage may contain not more than 10% added water.

4.2.3 Dairy Products

Despite the high-volume production of the milk industry, dairy products account for a relatively low share of 5% in process water usage. With a few exceptions, water only comes into direct contact with the products during sanitation of processing equipment.

In the case of fluid milk, process pipes and pumps are primed with water to facilitate startup. The first run of the water and milk mixture is discarded. Process water in the form of steam comes into direct contact with milk when the latter is heated by direct steam injection. Applications of this process include the deodorizing of milk (mostly used in the South to avoid garlic-like flavors caused by feed) and the heating of skim milk prior to drying. Culinary steam is also used in the manufacture of processed cheese when the shredded cheese is cooked with live steam for a weight gain of up to 6%. In these instances, however, the risk of contaminant carryover into the steam is greatly diminished.

Water may also be added directly during the processing of cheese in order to control texture characteristics; and in the form of brine during one continuous butter-making process.

4.2.4 Preserved Fruits and Vegetables

This category of food products accounts for the highest usage of process water in the U.S. food industry, or about one-third of total water used. The largest use is in the canning of fruits and vegetables, followed closely by freezing. This is no cause for surprise as much of the processing equipment, insofar as raw material preparation is concerned, is common to both industries.

Water is used to clean raw fruits and vegetables, and also to transport them between various process steps. It is also used to effect quality separation and facilitate further processing, and is added directly to canned goods in the form of brine, syrup or sauce, and to some frozen foods to prevent quality loss due to dehydration.

Water consumption can vary over wide limits, depending upon the physical characteristics of the raw material. In the canning industry, water use can range from a low of 300 gal/100 cases of finished product in No. 2 cans for sauerkraut to 25,000 gal/100 cases for lima beans (see Table 4-3). At a usage level of 7,000 gal/100 cases, tomatoes are fairly representative of the group as a whole.

TABLE 4-3. WATER REQUIREMENTS OF SELECTED CANNED PRODUCTS

Product	Total Water Consumption (gal/100 cases No. 2 cans)*
Apricots	8,000
Asparagus	7,000
Beets	2,500
Corn	2,500
Grapefruit juice	500
Grapefruit sections	5,600
Green beans	3,500
Lima beans	25,000
Peaches	6,500
Pears	6,500
Peas	2,500
Pork and beans	3,500
Pumpkin	2,500
Sauerkraut	300
Spinach	16,000
Squash	2,500
Succotash	12,500
Tomato products	7,000
Tomatoes, whole	750

*24 cans/case

Source: Jordan (1963).

Water enters the tomato processing operation together with the tomatoes at the rate of about 2500 gal of water per ton of tomatoes. About 10% of this water is initially used to soak the whole fruit so that contaminants are loosened on the surface. Following the soaking operation, about one-third of the water is used in a high-pressure spray to remove the surface contaminants. About 5% of the water is used to generate steam, part of which is used in direct contact to scale the tomatoes prior to peeling or pulping. The balance of the water is used to clean up the facilities and the processing equipment. The residual water contained in solid packed tomatoes or tomato juice is extremely small. Water is added as an ingredient in tomato sauces.

The quantities of water used in raw material preparation for dehydration compare closely with those for canning or freezing, on a per unit basis. In the case of pickle manufacture, the product is soaked in brine for a period of up to several weeks to ensure thorough penetration of the pickling solution.

4.2.5 Grain Milling Products

Despite the high volume and diverse nature of the products included in this industry group, process water usage accounts for 6% of the total food industry use.

Seventy percent of the group total is accounted for by the corn wet milling industry, which processes whole yellow corn into a wide variety of products such as corn starch, chemically modified starches, corn syrup, dextrose and high fructose corn syrup (HFCS); and by-products such as corn oil and animal feed.

Water is used extensively throughout the process. Cleaned corn is first steeped and softened in warm water tanks for several days. The "steepwater" or water drained off from this process, containing about 900 lbs solid matter per 1000 gal, is a good protein source, and is converted to animal feed or used as a fermentation nutrient after concentration. The kernels are subsequently milled to remove the corn germs, which are washed and separated by flotation.

After subsequent grinding operations, starch is removed from the gluten by flushing with water. The starch is finally cleaned by a series of washings and filtering processes; the wash water is re-used in earlier stages of the process.

Rice milling is somewhat similar, insofar as a hot water steeping process may be used to condition the product prior to milling.

Dog, cat, and other pet foods include moist and semi-moist product categories. In both of these instances, water is used in product formulation to a greater or lesser extent, as well as coming into indirect contact with the product during processing line cleanup operations.

Cereal breakfast foods can also be classified into two general types: those made from whole grains or their mill products, and those made from fabricated cereal products. Considerable variations exist within each type in regard to the cereals and other raw materials used, and the type of processing employed. The grains may be cooked in steam, while water may form part of the formulation in dough preparation or flavoring system.

A small quantity of water is used in the flour milling industry to wash the wheat, which is then passed through a centrifuge to remove excess moisture. A further addition of water may be made to condition the wheat prior to subsequent milling operations. This toughens the bran and assists separation.

4.2.6 Bakery Products

Bakery products take only 1% of the total process water consumed by the U.S. food industry. Process water usage is largely accounted for by dough manufacture--typically about 40 lbs of water are required for every 66 lbs of flour in order to prepare a bread dough. Similarly, cakes and other bakery products incorporate water to a greater or lesser extent in their formulation.

Water is also used in pan washing, and in cleaning other equipment and utensils.

Cookie and cracker production is fairly similar to bread production, except that in general stiffer doughs are prepared, and so the quantity or process water used is less.

4.2.7 Sugar, Confectionery Products

This industry group accounts for 8% of total food industry use of process water. Most of this occurs in raw cane sugar and beet sugar processing operations.

Large quantities of water are used in raw cane milling. A typical cane sugar mill processes about 2,000 tons of sugar cane per day. Around 22% of this quantity is required in inhibition water. This is water that is added to the cane while it is being passed through the crushing rollers. The water mixes with the raw juice, which is subsequently concentrated by evaporators.

A cane sugar refinery produces white crystalline sugar from the raw sugar resulting from the milling operation. Sugar cake is washed in hot water, and the crystals are then dissolved in about one-half their weight of hot water, prior to recrystallization. The process requires a water consumption of about 0.5 gal for every pound of sugar refined.

In the processing of sugar beets, the raw material is conveyed to the initial stages of production by water channels or flumes. Water sprays are used in rotary beet washers, where gross contamination is removed. The beets are then sliced and passed into a diffusor, where the sugar is extracted with hot water. Flow rates are high, as a large sugar beet operation may process about 6,500 tons of beets per day. The refining operation is very similar to that described for cane sugar.

4.2.8 Fats and Oils

Fats and oils only account for about 1% of food industry use of process water.

Most lard and edible tallow produced in the United States is made by the high-temperature wet rendering process. Water and fatty material are introduced into an autoclave or digester. The high pressure steam is turned on and pressure is maintained for several hours. Under these conditions, a high yield of fat is obtained.

Water is also used in the continuous alkali refining of crude oils. The refined oil is washed with hot water to remove residual soap.

Fairly large quantities of water in the form of injected steam are used for deodorization of edible fats and oils. Typically, 25 lbs of injected steam per 100 lbs fat are required for this operation.

4.2.9 Beverages

A broad variety of alcoholic and non-alcoholic beverages account for 15% of U.S. food industry process water consumption. Malt beverages alone account for two-thirds of this amount.

A typical brewery consumes large amounts of process water, resulting from an annual production of around 5 million barrels of beer (of 31 gal each) containing about 90% water.

The largest process water usage is incurred at the first stage of brewing when a cereal/malted barley mash is boiled in water. A typical mash contains about 100 lbs of cereal and about 100 lbs malted barley for each barrel of water. Large quantities of water also come into indirect contact with the product in such applications as bottle and barrel washing and sanitizing operations. The total water consumption amounts to 570 gal per barrel of beer.

The production of the malted barley ingredient also calls for water, which is used to steep the grain in drums or on malting floors to effect germination.

The soft drinks industry also uses a high volume of process water as the bottled and canned products also contain about 90% water. Water is used in the manufacture of simple syrup, a basic soft drink ingredient;

and in the preparation of cooled carbonated water, the other major formulation component. Water also comes into direct contact with the product through its use in can and bottle washing, as well as in the sanitizing of equipment and utensils.

The production of distilled liquors generally involves mashing the grain or other fermentable raw materials with hot water as the first step in the process. After distillation, the beverage is adjusted to the desired proof or alcoholic strength by the addition of plain or distilled water.

In the case of wines and related products, the use of water is limited to indirect contact applications such as bottle washing and sanitizing equipment, with the exception of certain wines based on fruit other than grapes, such as blackberries and peaches, where water is used in product formulation.

4.2.10 Miscellaneous Foods

This final category accounts for 4% of total process water consumption and is dominated by the processing of fresh, frozen, canned, and cured seafoods.

Liberal use of water is made at all stages of fish processing, including gutting, filleting, cooking, and canning in brine or sauce. Water comes into contact with whole fish and fillets in the form of ice, which is added to slow down the rate of deterioration of the product before the preservation process. Extensive use is made of water in process line cleanup.

In addition to making ice for commercial fish harvesting and processing operations, ice makers manufacture and sell ice for institutional, wholesale and retail customers.

The coffee industry uses water in the manufacture of soluble coffee. Ground, roasted coffee is extracted with hot water, and then the resulting liquid is evaporated or spray dried to a powder.

Macaroni and spaghetti is produced from a dough containing semolina, durum flour, water, and other ingredients. This category represents one of the lowest demands for process water in the U.S. food industry.

4.3 SUMMARY OF WATER USE DURING PROCESSING

Table 4-4 contains a summary of water use during processing by food industry group. It identifies the process in which water has direct contact with the food. The text has discussed quantities of water associated with most of these particular steps and the conditions of contact using representative examples. For instance, the following breakdown was derived for tomatoes:

TABLE 4-4. DIRECT FOOD/WATER CONTACT DURING PROCESSING BY FOOD INDUSTRY GROUP

FOOD INDUSTRY GROUP / PROCESS	Drinking Troughs	Process Line Priming	Raw Material Wash	Raw Material Transport	Extract	Peel	Heat	Cool	Cure	Deodorize	Product Formulation	Quality Separation	Cleanup
Meat Products													
Meatpacking	•		•										•
Poultry			•					•					•
Sausages/Prepared Meats			•						•		•		•
Dairy Products													
Fluid Milk		•					•			•			•
Cheese											•		•
Fruits, Vegetables													
Canned/Frozen			•	•		•					•	•	•
Pickles			•						•		•		•
Grain Milling													
Corn Wet Milling			•		•								
Pet Foods											•		•
Breakfast Cereals							•				•		•
Flour Milling			•			•							
Bakery Products													
Bread											•		•
Cookies											•		•
Sugar, Confectionery													
Cane Sugar			•		•								
Beet Sugar			•	•	•								
Fats, Oils													
Animal/Vegetable Oils			•		•					•			•
Beverages													
Malt Beverages					•						•		•
Soft Drinks											•		•
Distilled Liquor					•						•		•
Wines											•		•
Miscellaneous													
Canned Seafood			•				•	•			•		•
Frozen Seafood			•				•	•			•		•
Roasted Coffee					•								
Macaroni/Spaghetti											•		•

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process	water contact (gal/ton product)
soak	250
spray	800
steam	125

These values cannot be summed to obtain a total water contact since these processes involve different types of contact. A model could be developed as for food during growth, however, several factors need to be taken into consideration before amounts of contaminants entering food can be estimated.

- Detailed assessment of the surface area contacted, and the time of contact. This would vary by crop and process step.

- Consideration of the rates of absorption or adsorption of water or the pollutant under the conditions specified for each processing step.

Thus, although the opportunities for water contact can be specified, this information cannot yet be used for calculating the resultant concentrations of a water-borne pollutant in processed food.

5.0 WATER-RELATED CONTAMINATION OF FOOD DURING HOME PREPARATION

Food may be contaminated with water-borne pollutants in the home during washing and cooking. Food preparation processes that require substantial amounts of water are boiling, steaming, stewing, and water mixing. The foods that are normally prepared by one or more of these methods (including washing) are listed in Table 5-1, as well as estimates of water consumption.

In terms of water actually consumed, mixing with water is the largest user of water among the five methods listed. Stewing and boiling provide ample opportunity for water-borne contaminants to enter food (and subsequently be ingested), particularly if the added water is retained (e.g., in stews, rice, and pasta). Steaming in all likelihood does not entail significant exposure of food to pollutants, partly because of the small quantities of water used, and partly because many inorganic contaminants do not evaporate readily. Washing presents minimal potential for contamination, because of the relatively brief contact of the food with water.

The problems with utilizing these data as a basis for estimating actual concentrations are the same as those mentioned previously for food processing. The data requirements for a model are the same for commercial preparation as home preparation; thus, a model could be developed using similar considerations. For products, such as jello, to which water is added directly (see water mixing in Table 5-1), volumes can be used with concentrations in water to estimate concentrations in those particular foods. As an example, humans are generally considered to consume about 2 l/day of tap water as drinking water and in water-based drinks (coffee, tea). If a person were to consume such items as dried milk, powdered eggs, soup, hot cereal, rice, jello and frozen juice, they might consume about 1.8 l of water with these products. Thus, intake of a pollutant from drinking water could be comparable to intake resulting from consumption of these products.

TABLE 5-1. ESTIMATED WATER USE IN HOME PREPARATION OF FOOD

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Food Group	Water Use (oz) per Unit of Preparation				
	Boiling	Steaming	Water Mixing	Stewing	Washing
Fresh Vegetables					
Lettuces					64 oz./head
Root vegetables	32 oz./lb.				32 oz./lb.
Spinach, cabbages, broccoli	32 oz./lb.	8 oz./lb.			64 oz./lb.
Legumes	32 oz./lb.	8 oz./lb.		16 oz./lb.	64 oz./lb.
Tomatoes, peppers	16 oz./lb.			16 oz./lb.	32 oz./lb.
Squashes	32 oz./lb.			16 oz//lb.	
Corn	48 oz./lb.				
Frozen Vegetables	8 oz./12 oz. pkg.				
Canned Vegetables	8 oz./can				
Freeze-dried Vegetables			16 oz./4 oz. pkg.		
Fresh Fruits					32 oz./lb.
Berries			16 oz./4 oz. pkg.	48 oz./lb.	32 oz./lb.
Fresh Fruits				16 oz./lb.	32 oz./lb.
Dairy Products					
Dried Milk			32 oz./5 oz. pkg.		
Condensed Milk			16 oz./can		
Powdered Eggs			16 oz./pkg.		

TABLE 5-1. ESTIMATED WATER USE IN HOME PREPARATION OF FOOD (Continued)

Food Group	Water Use (oz) per Unit of Preparation				
	Boiling	Steaming	Water Mixing	Stewing	Washing
Meats					
Fresh (all meats)	32 oz./lb.	8 oz./lb.		64 oz./lb.	
Poultry, fresh fish					16 oz./lb.
Freeze-dried (all meats)			16 oz./4 oz. pkg.		
Prepared Foods					
Dry Soup Mix			24 oz./pkg.		
Condensed Soup			11 oz./can		
Single Serving Soups			8 oz./pkg.		
Boullion Cubes	8 oz. cube				
Hot Breakfast Cereals	6 oz./serving		6 oz./serving		
Rice	16 oz./cup				
Pasta	150 oz./lb.				
Baking Mixes			12 oz./pkg.		
Gelatin, Instant Pudding			16 oz./pkg.		
Drinks					
Frozen Juices			48 oz./12 oz. can		
Tea Bags			12 oz./bag		
Loose Tea			16 oz./ tsp.		
Instant Tea			8 oz./tsp.		
Ground Coffee			12 oz./tsp.		
Instant Coffee			6 oz./tsp.		
Powdered Mixes			48 oz./pkg.		

Source: Arthur D. Little, Inc. estimates.

6.0 DRINKING WATER CONTAMINATION DURING TREATMENT AND DISTRIBUTION

6.1 INTRODUCTION

Much emphasis has been placed on the contamination of drinking water supplies, and only recently has contamination in drinking water treatment and distribution been considered as a source of human exposure to hazardous chemicals. This Chapter examines such types of exposure. Unlike food contamination, drinking water contamination during treatment and distribution is generally limited to certain types of chemicals. Chemicals introduced in water treatment and distribution come in direct contact with the water supply and predicting the resultant contamination requires specific information on water chemistry and other environmental conditions. This Chapter considers qualitatively the types of such contamination that may occur and the conditions that promote the occurrences.

Figure 6-1 shows the flow of drinking water from the water supply to the consumer. Several sources of contamination have been identified, including chemical additions at the treatment plant, chemical production at the treatment plant, pipe corrosion, and leakage into pipes. These types of contamination will be discussed individually below.

6.2 CHEMICAL ADDITIONS AT THE TREATMENT PLANT

Thousands of chemicals are used in water treatment in the U.S. today. The U.S. EPA has compiled a long list of approved additives, however, has no regulatory authority except through the individual states. Thus, although the composition of some additives is very well known, i.e., chlorine, the composition of others is largely unknown. In addition, even the known chemical additives may contain trace contaminants that have not yet been identified.

With the exception of chlorine and florine, most chemicals added at the treatment plant are not intended to remain in the finished drinking water. Nevertheless, little is known about the fate of these chemicals, and especially the fate of any contaminants.

6.3 CHEMICAL FORMATIONS AT THE TREATMENT PLANT

The chlorination of drinking water results in the formation of chlorinated organics, particularly trihalomethanes. The production of these compounds, especially chloroform, appears to depend primarily on the available precursors. Arguello *et al.* (1979) reported that such compounds in raw water as resourcinol, 4-methoxyphenol, humic acid, 2,6-dimethylphenol, pentachlorophenol, hydroquinone and n,n-diethylaniline in raw water resulted in a high production of chloroform. The production of bromoform was directly related to the bromide concentrations in raw

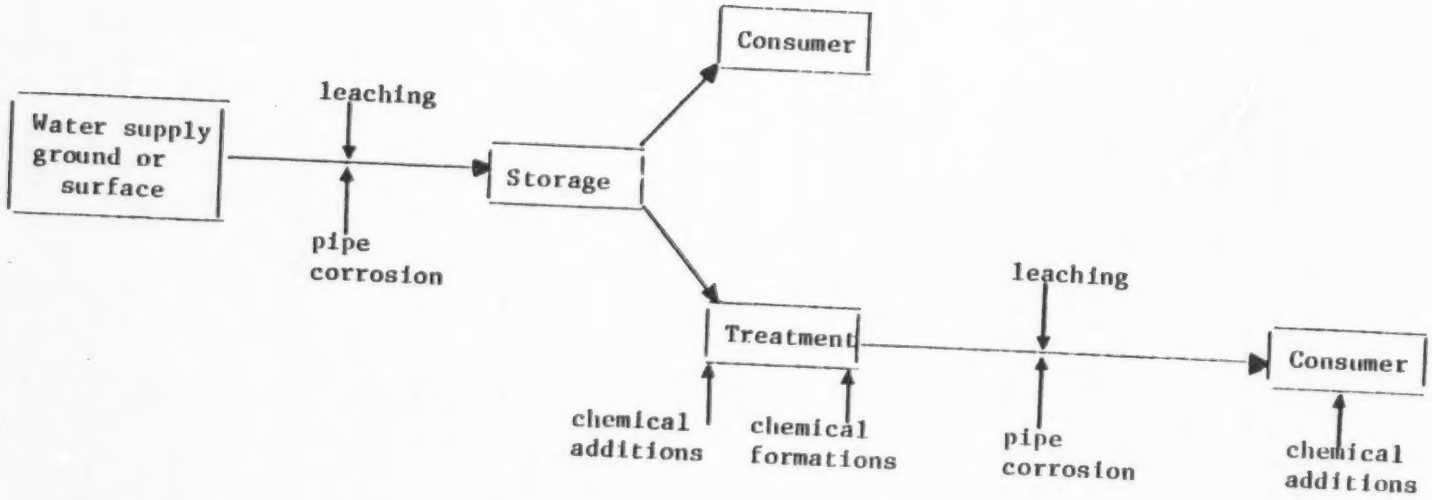

FIGURE 6-1. SOURCES OF CONTAMINATION OF DRINKING WATER IN TREATMENT AND DISTRIBUTION

water. Temperature appears to influence the production of trihalomethanes, usually resulting in a lower production at lower temperatures. In addition, trihalomethanes continue to be formed in the distribution system if the water contains a chlorine residual, an appropriate precursor, or both (Brett and Claverley 1979).

The estimation of trihalomethane concentrations, based on these variables is complex. While production ratios (from precursors) have been calculated in the laboratory, these ratios are not useful in the field for predictive purposes. The primary reason for this is that in the field a composite of precursors will be available, and production ratios are not likely to be the same as in the isolated laboratory situation.

6.4 PIPE CORROSION

Pipe corrosion is a well-known problem in water distribution, and the release of metals from lead pipes into the drinking water has been studied extensively. However, other chemicals may be released in the distribution, such as vinyl chloride and asbestos if PVC or asbestos-cement piping is used. This section will discuss these types of distribution systems and the resulting contaminants.

6.4.1 Metal Pipes

The release of metals from distribution systems depends on the water quality and the piping material used. Important water quality parameters influencing corrosion are pH, alkalinity, hardness, temperature, dissolved oxygen and dissolved carbon dioxide (McFarren et al 1977). In general, soft waters containing dissolved oxygen and carbon dioxide promote corrosion, especially at higher temperatures (Karalekas et al. 1976).

Distribution systems have most commonly been examined from a materials point of view, that is, the corrosion is measured as loss in diameter in mils per year. Though this is a quantitative measure of loss, it bears little relationship to concentrations of metals that may result in the water. Table 6-1 shows types of plumbing used and the metals that may be released. These types of materials corrode at different rates under different conditions and the rate of corrosion is not predictable.

Even for the same water system, concentrations vary depending on the time of day. For example, the maximum sample taken in a survey of homes in the Boston area showed 1.5 mg/l lead in a standing sample (the water was standing in the pipes for several hours). In a running sample (the water is run for several minutes before sampling) the level of lead was 0.13 mg/l, a difference of a factor of ten (Karalekas et al. 1976).

TABLE 6-1. METALS IN DRINKING WATER RESULTING FROM VARIOUS TYPES OF PLUMBING

Type of Plumbing	Resultant Metal in Drinking Water	Concentrations Found[a]
Lead	Lead	Pb - 170-1500 ug/1
Zinc-lined galvanized iron	Lead, zinc, cadmium	Pb - 3.2-24.1 ug/1, Cd <0.04-0.2 ug/1, 2n-280-1400 ug/1.
Alloys (solder, brass, bronze)	Copper, lead, silver, zinc	
Iron and steel	Iron, manganese	
Copper and brass	Copper	
Stainless steel	Chromium, nickel	

[a]pipe exposed to corrosive water and standing water.

Sources: Karalekas et al. (1976) and McFarren et al. (1977).

While most metals are leached from the piping material, as is shown in the example given above, small amounts of lead or other metal may come from other sources such as lead joints, gaskets and lead-tin solder used in the system. Though these sources probably represent insignificant sources as compared with lead pipes, they may significantly contribute to lead levels where other types of piping are used.

6.4.2 Asbestos-Cement Pipes

Asbestos-cement pipe is commonly used in the United States in water distribution systems. Hallenbeck et al. (1978) reported that one-third of all water distribution pipe sold at that time in the U.S. was asbestos-cement.

Recently, the release of asbestos into drinking water in the distribution has been observed (Sargent 1974; Peterson 1978, McFarren et al. 1977). The American Water Works Association Standard C400-77 sets criteria for quality of water that can be transported through asbestos-cement pipe using the equation pH + log AH, where A equals the alkalinity (mg/l as $CaCO_3$). This equation is used to determine the agressiveness of the water. Values greater than 12 are non-aggressive, 10.0-11.9 are moderately aggressive, and less than 10 are considered highly aggressive. The use of this equation implies that the release of asbestos is related directly to these parameters.

While pH, hardness and alkalinity may influence the release of asbestos from pipes, other factors are also important. For example, Buelow et al. (1979) have shown that zinc, iron, and manganese in the water can provide protection against asbestos release. On the other hand, mechanical handling during installation and tapping for new users promote release, if only temporarily. In addition, a high H_2S content in the source water was associated with higher levels of asbestos in drinking water.

Obviously the release of asbestos from piping is a largely unpredictable event. Levels may vary within a system at different times. Therefore, calculating asbestos levels resulting in drinking water would be extremely difficult.

Liners of concrete pipes can also be a source of pollutants in drinking water. Tetrachloroethylene has been reported at levels up to 5 mg/l in drinking water in Massachusetts. These levels were caused by leaching from a resinous liner of concrete pipes used in distribution systems (DEQE 1980).

6.4.3 PVC Pipes

Polyvinyl chloride (PVC) pipe has been used in distribution systems for a number of years. Though it has not been studied extensively, PVC pipe has generally been considered stable. Flexible PVC, however, has been shown to release a number of organic materials, including numerous

phthalate esters (Junk et al. 1974). In addition, Dressman and McFarren (1978) have observed the migration of vinyl chloride from PVC into water. Little is known about the factors affecting such migration, but it does not seem to depend as much upon water chemistry as does the migration from metal pipes.

In addition to vinyl chloride, Wang and Bricker (1979) identified MEK (2-butanone) and THF (tetrahydrofuran) in a water supply after PVC pipes were installed. These solvents were used in the PVC pipe cement used to join the tubing. The concentrations in this particular case depended upon the residence time, up to an equilibrium concentration.

Clearly too little is known at present about the release of contaminants from the PVC pipe to describe even the conditions that promote it.

6.5 ACCIDENTAL CONTAMINATION IN THE DISTRIBUTION SYSTEM

Accidental contamination of drinking water in the distribution system may occur in a number of ways, including cross-connections, back-siphonage, and breaks in the system. The contaminants that may result are limitless, and do not depend upon the characteristics of the water, the distribution system, or the chemical. As a typical example of what may occur, Craun and Gunn (1979) described an incident in which chlordane applied to a home for termite control had entered a water distribution system due to back-siphonage. It was hypothesized that during preparation and dilution of the solution, back-siphonage occurred and chlordane entered the distribution system.

Obviously, this type of incident cannot be predicted, nor can the situations in which it would occur be described.

6.6 SUMMARY

Some of the important routes of contamination in drinking water treatment can be described qualitatively as shown in Table 6-2. In some cases the conditions that may promote release or contamination are known but in no case can the estimated resulting concentrations of water-borne pollutants be calculated.

TABLE 6-2. CONTAMINATION OF DRINKING WATER IN TREATMENT AND DISTRIBUTION

Contamination Route	Chemicals Involved
Treatment:	
Chemical addition	Large number, chlorine and fluoride common
Chemical formation	Trihalomethanes, other chlorinated organics
Distribution:	
Pipe Corrosion	Metals, asbestos, vinyl chloride
Cross-connection, back-siphonage	Unknown

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